(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 0 805 487 A2

(12) # EUROPEAN PATENT APPLICATION

(43) Date of publication:
05.11.1997 Bulletin 1997/45

(51) Int Cl.6: H01L 21/68

(21) Application number: 97302806.1

(22) Date of filing: 24.04.1997

(84) Designated Contracting States:
AT BE CH DE ES FR GB GR IE IT LI NL SE

(30) Priority: 02.05.1996 US 641938

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(54) **Multielectrode electrostatic chuck with fuses**

(57) A failure resistant electrostatic chuck **20** for holding a substrate **35** during processing of the substrate **35**, is described. The chuck **20** comprises a plurality of electrodes **25** covered by an insulator **30**, the electrodes **25** capable of electrostatically holding a substrate **35** when a voltage is applied thereto. An electrical power bus **40** has a plurality of output terminals **45** that conduct voltage to the electrodes **25**. Fuses **50** electrically connect the electrodes **25** to the output terminals **45** of the power bus **40**, each fuse **50** connecting at least one electrode **25** in series to an output terminal from the power bus **40**. The fuses **50** are capable of electrically disconnecting the electrode **25** from the output terminals **45** when the insulator **30** punctures and exposes the electrode **25** to the process environment causing a current to flow through the fuse **50**. A current detector **175** and electrical counter **180** can be used to provide early detection and counting of the number of failures of the electrodes **25** by detecting the current discharges through the fuses **50**.

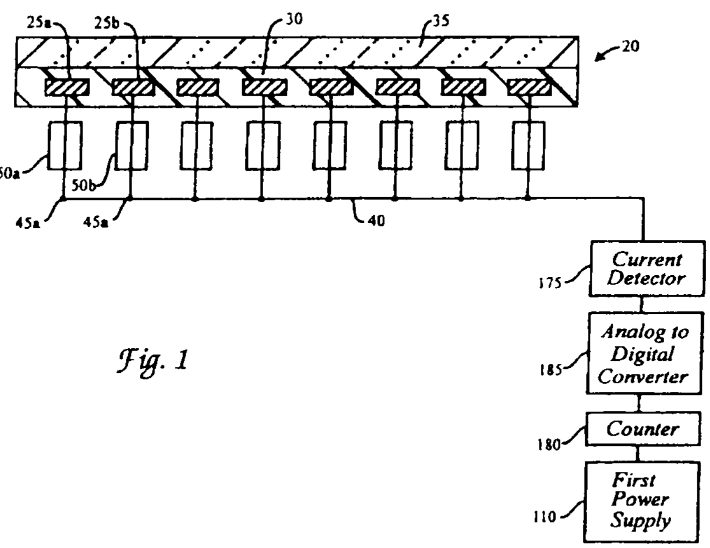

Fig. 1

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electrodes.

In another configuration, useful for holding substrates in non-plasma processes, the electrostatic chuck comprises first and second groups of electrodes covered by insulator, the electrodes sized and configured to serve as bipolar electrodes and capable of electrostatically holding a substrate when a voltage is applied thereto. A first electrical power bus has a first set of output terminals for providing voltage to the first group of electrodes, and a second electrical power bus has a second set of output terminals for providing voltage to the second group of electrodes. A plurality of fuses is provided, each fuse electrically connecting at least one electrode in series to an output terminal from a power bus. The fuses are capable of electrically disconnecting the electrodes from the output terminals when the insulator punctures and exposes the electrodes to the process environment, causing a current to flow through the fuse.

In another aspect of the invention, the electrodes of the chuck comprise (i) peripheral electrodes in a periphery of the insulator, and (ii) central electrodes in a central portion of the insulator. A first power bus has a first set of output terminals that provides voltage to the peripheral electrodes, and a second power bus has a second set of output terminals that provide voltage to the central electrodes. Fuses electrically connect the electrodes in series to output terminals from the power buses and are capable of electrically disconnecting the electrodes from the output terminals when the insulator punctures and exposes the electrodes to the process environment causing a current to flow through the fuse. This version allows early replacement of the chuck when any one of the peripheral electrodes is exposed to the plasma environment, the peripheral electrodes being particularly important to prevent leakage of heat transfer fluid held below the chuck.

The present invention also provides an electrostatic chuck system that allows early detection, and optionally counting, of failure of electrodes of the electrostatic chuck. This system uses a current detector to detect current flow through the fuses, the current flow occurring when insulator on an electrode punctures and allows the electrostatic charge in the substrate to discharge as a current through the electrode and contiguous fuse. The current detector deflects the current discharge before the fuse electrically disconnects the electrode from the output terminal of the fuse. Preferably, the system further comprises a counter for counting the number of times current discharges through the fuses, providing an estimate of the number of failed electrodes, to allow replacement of the chuck before catastrophic failure of the chuck.

The present invention further teaches methods for forming the failure resistant electrostatic chucks. One method comprises the steps of (a) selecting a first insulator layer, (b) forming electrodes, electrical power buses, and fuses on the first insulator layer, and (c) forming a second insulator layer over the electrodes, electrical power buses, and fuses. In another method, the electrostatic chuck can be fabricated using a composite layer including (i) a first insulator layer, (ii) a resistor layer, and (iii) an electrical conductor layer. The composite layer is etched to form the electrodes and electrical power buses from the electrical conductor layer, and the resistors from the resistor layer. Each of the resistors serves as a fuse and electrically connecting at least one electrode to an electrical power bus. A second insulator layer is formed over the etched composite layer to fabricate the chuck.

The features, aspects, and advantages of the present invention will become better understood with regard to the following description, appended claims, and accompanying drawings which illustrate versions of the invention, where:

Figure 1 is a partial sectional schematic side view of an electrostatic chuck of the present invention;

Figure 2 is a partial sectional schematic side view of a process chamber showing operation of an electrostatic chuck of the present invention;

Figure 3 is a partial sectional schematic side view of a process chamber showing operation of a bipolar electrostatic chuck of the present invention;

Figure 4 is a cross-sectional schematic side view of another embodiment of an electrostatic chuck of Figure 1;

Figure 5 is a cross-sectional schematic side view of another embodiment of an electrostatic chuck of Figure 1;

Figure 6 is a cross-sectional schematic side view of another embodiment of an electrostatic chuck of Figure 1;

Figure 7 is a cross-sectional schematic side view of another embodiment of an electrostatic chuck of Figure 1;

Figures 8a-8f are sectional schematic side views showing successive steps in the fabrication of a version of the electrostatic chuck of the present invention;

Figure 9a is a schematic top view of an electrode, power bus, and fuse assembly of the electrostatic chuck manufactured using the process illustrated in Figures 8a-8f;

Figure 9b is an enlarged schematic view of the inset box 9b of Figure 9a showing details of the electrode, power bus, and fuse assembly;

Figure 10 is a schematic top view of a bipolar electrostatic chuck having two semicircular groups of electrodes; and

Figure 11 is a schematic top view of another bipolar electrostatic chuck having a double ring electrode configuration.

The present invention is useful for multielectrode structures, such as capacitors, batteries, and electrostatic chucks. Although the present invention is illustrated in considerable detail in the context of an electrostatic chuck useful for holding substrates in process environments, many other versions of the invention should be apparent to those skilled in the art, without deviating from the scope of the invention. Therefore, the spirit and scope of the present invention should not be limited to the description of the preferred versions contained herein.

As schematically illustrated in Figure 1, an electrostatic chuck **20** of the present invention comprises a plurality of monopolar or bipolar electrodes **25a**, **25b** covered by a layer of insulator **30**. The electrodes **25a**, **25b** capable of electrostatically holding a substrate **35** when a voltage is applied to the electrodes **25a**, **25b**, as described below. An electrical power bus **40** comprises a plurality of output terminals **45a**, **45b** for conducting voltage to the electrodes **25a**, **25b**. Fuses **50a**, **50b** electrically connect the electrodes **25a**, **25b** to the output terminals **45a**, **45b** of the power bus **40**. Each fuse **50a** connects at least one electrode **25a** in series to an output terminal **45a** and is capable of electrically disconnecting the electrode **25a** from the output terminal **45a** when the insulator **30** over the electrode punctures and exposes the electrode to the process environment causing a current to flow from the electrode **25a** and through the fuse **50a**.

As illustrated in Figure 2, the electrostatic chuck **20** is secured on a support **60** in a process chamber **65** that forms an enclosure for processing of the substrate **35**. The process chamber **65** typically includes a process gas source **70** for introducing process gas into the chamber **65**, and a throttled exhaust **75** for exhausting gaseous byproducts from the chamber **65**. The particular embodiment of the process chamber **65** shown in Figure 2 is suitable for plasma processing of substrates **35**; however, the present invention can be used with other process chambers or processes without deviating from the scope of the invention.

Typically, the electrostatic chuck **20** comprises a base **80**, with a bore **85** therethrough, that is useful for supporting the electrodes **25** and insulator **30**. An electrical connector **90** electrically connects the power bus **40** to a voltage supply. The electrical connector **90** comprises (i) an electrical lead **95** that extends through the bore **85** of the base **80**, and (ii) an electrical contact **100** that electrically engages a voltage supply terminal **105** at the interface between the base **80** and the support **60**. A first voltage supply **110** provides an electrical voltage to the voltage supply terminal **105** for operating the chuck **20**. The first voltage supply **110** typically includes a circuit which comprises a high voltage DC source of about 1000 to 3000 volts, connected to a high voltage readout, through a 10 MΩ resistor. A 1 MΩ resistor in the circuit limits current flowing through the circuit, and a 500 pF capacitor is provided as an alternating current filter.

A second voltage supply **115** is connected to the support **60** in the process chamber **65**. At least a portion of the support **60** is typically electrically conductive and functions as a process electrode, or cathode, for forming a plasma in the chamber **65**. The second voltage supply **115** is provided for electrically biasing the support **60** with respect to an electrically grounded surface **120** in the chamber **65**, to form an electric field that generates and/or energizes a plasma formed from the process gas in the chamber **65**. An insulative flange **125** is disposed between the support **60** and the grounded surface **120** to electrically isolate the support **60** from the grounded surface **120**. The second voltage supply **115** generally comprises an RF impedance that matches the impedance of the process chamber **65** to the impedance of the line voltage, in series with an isolation capacitor.

To operate the chuck **20**, the process chamber **65** is evacuated and maintained at a sub-atmospheric pressure. A substrate **35** is placed on the chuck **20**, and the electrodes **25** of the chuck **20** are electrically biased with respect to the substrate **35** by the first voltage supply **110**. Thereafter, process gas is introduced into the chamber **65** via the gas inlet **70**, and plasma is formed from the process gas by activating the second voltage supply **115** or by using alternative plasma generator sources, such as inductor coils (not shown). The voltage applied to the electrodes **25** causes electrostatic charge to accumulate in the electrodes **25**, and the plasma in the chamber **65** provides electrically charged species having opposing polarity which accumulate in the substrate **35**. The accumulated opposing electrostatic charge results in an attractive electrostatic force that electrostatically holds the substrate **35** to the chuck **20**.

To regulate the temperature of the substrate **35** held on the chuck **20**, a heat transfer fluid source **140** can be used to supply heat transfer fluid to grooves **145** in the insulator **30**. The substrate **35** held on the chuck **20** covers and seals the grooves **145**, preventing heat transfer fluid from leaking out. The heat transfer fluid in the grooves **145** can be used to heat or cool the substrate **35** to regulate the temperature of the substrate **35** and maintain the substrate **35** at constant temperatures during processing. Typically, the grooves **145** form a pattern of intersecting channels extending through the insulator **30**.

The multielectrode chuck **20** of the present invention is resistant to failures occurring from erosion or puncture of the insulator **30** on the electrodes **25**. When a sharp-edged fragment punctures the insulator **30** cov-

ering an electrode **25a**, the electrostatic charge in the substrate **35** flows through the exposed electrode **25a** and through the fuse **50a** connected to the electrode. The current flowing through the fuse **50a** as a result of the electrostatic discharge causes the fuse **50a** to automatically switch-off in a relatively short time to electrically disconnect the electrode **25a** from the output terminal **45a** of the electrical power bus **40**. However, the remaining electrodes **25b**, **25c** which are still insulated by the insulator **30** provide a large contact area of electrodes that continues to operate and electrostatically hold the substrate **35** to the chuck **20**. Thus, each fuse **50a** and electrode **25a** assembly functions as an independently operated micro electrostatic chuck having a small contact area, and obtains its power supply from an independently powered output terminal **45a** of the power bus **40**. In this manner, the electrostatic chuck **20** of the present invention provides significant advantages by continuing to hold the substrate **35** and resisting catastrophic failure even when the insulator **30** covering an electrode **25** is punctured or eroded.

A bipolar version of the electrostatic chuck **20** of the present invention will now be described with reference to Figure 3. In the bipolar version, the chuck **20** comprises an insulator **30** covering a first group of electrodes **146** and a second group of electrodes **148**, sized and configured to serve as bipolar electrodes. The groups of electrodes **146**, **148** are capable of electrostatically holding a substrate **35** when a voltage is applied thereto. A first power bus **40a** having a first set of output terminals **45a** provides voltage to the first group of electrodes **146**. A second power bus **40b** having a second set of output terminals **45b** provides voltage to the second group of electrodes **148**. A plurality of fuses **50a**, **50b** are provided, each fuse **50a** electrically connecting at least one electrode **25a**, **25b** in series to an output terminal **45a**, **45b** from a power bus **40a**, **40b**. The fuses **50a**, **50b** are capable of electrically disconnecting the electrodes **25a**, **25b** from the output terminals **45a**, **45b** when the insulator **30** punctures and exposes the electrodes to the process environment causing a current to flow through the fuse **50**.

In the bipolar version, the first voltage supply **110** provides a differential electrical voltage to the first and second power buses **40a**, **40b**. In a preferred configuration, the first voltage supply **110** comprises two DC power supplies that provide a negative voltage to the first electrodes **146** and a positive voltage to the second electrodes **148** to maintain the electrodes at a differential electric potential relative to one another. The opposing electric potentials of the groups of electrodes **146**, **148** induce opposing electrostatic charges in the groups of electrodes **146**, **148**, and in the substrate **35** held to the chuck **20**, without use of a plasma in the process chamber **65**, causing the substrate **35** to be electrostatically held to the chuck **20**. Bipolar electrode configurations are advantageous for non-plasma processes in which there are no charged plasma species to serve as charge carriers for electrically biasing the substrate **35**.

Alternate versions of the chuck **20** that allow ease of fabrication, increased reliability, and maximization of the electrostatic clamping force generated by the electrodes will now be described. In the version illustrated in Figure 4, the electrical power bus **40** comprises an planar conductive layer spaced apart from the electrodes **25** that provides voltage for operating the electrodes **25**. Each fuse **50** electrically connects, in series, at least one electrode **25** to the power bus **40**. Preferably, the fuses **50** comprise a resistive coating **150** on a hole **155** that extends between an electrode **25** and the planar conductive layer, the resistive coating **150** comprising, for example, a thin coating of a conductive or resistive material that serves as a resistor element. This version has certain advantages of fabrication, because the resistive fuse elements can be easily fabricated by depositing the resistive coating **150** on holes **155** formed in an insulator **30** covering the planar conductive layer.

In the version shown in Figure 5, the output terminals **45** of the electrical power bus **40** are substantially coplanar with the electrodes **25**. The electrodes **25** are coplanar so that the electrostatic contact area of the electrodes **25** fall in a single plane. The output terminals **45** are positioned coplanar to the electrode plane, and lie between and spaced apart from the electrodes **25**. This arrangement allows the fuses **50** to be positioned in between the electrodes **25**, thereby reducing the total thickness of the electrode **25** and insulator layer **30**, and maximizing the attractive electrostatic force of the chuck **20**.

In the configuration shown in Figure 6, the electrical connector **90**, electrical power bus **40**, and fuses **50**, form a unitary structure. An electrical conductive plate has (i) an exposed portion that serves as the electrical contact **100**, and (ii) an insulated portion on the opposing side of the exposed electrical contact **100** serves as the electrical power bus **40**. The fuses **50** are embedded in the insulated portion opposing the exposed electrical contact **100** and are electrically connected to the output terminals **45** of the power bus **40**. The electrically conductive plate with the insulated fuses **50** and power bus **40** forms an unitary structure that can be easily replaced when the fuses burn-out.

In the version shown in Figure 7, the chuck **20** comprises (i) peripheral electrodes **160** in a periphery of the insulator **30**, and (ii) central electrodes **165** in central portion of the insulator **30**. A first power bus **40a** having a first set of output terminals **45a** provides voltage to the peripheral electrodes **160**, and the second power bus **40b** having a second set of output terminals provides voltage to the central electrodes **165**. Fuses **50a**, **50b** electrically connect the electrodes **160**, **165** in series to output terminals **45a**, **45b** from the power buses **40a**, **40b**, as shown. The fuses **50a** are capable of electrically disconnecting the peripheral electrodes **160** from the power bus **40a** when any one peripheral electrodes **160** is exposed to the process environment. This version al-

ering an electrode **25a**, the electrostatic charge in the substrate **35** flows through the exposed electrode **25a** and through the fuse **50a** connected to the electrode. The current flowing through the fuse **50a** as a result of the electrostatic discharge causes the fuse **50a** to automatically switch-off in a relatively short time to electrically disconnect the electrode **25a** from the output terminal **45a** of the electrical power bus **40**. However, the remaining electrodes **25b**, **25c** which are still insulated by the insulator **30** provide a large contact area of electrodes that continues to operate and electrostatically hold the substrate **35** to the chuck **20**. Thus, each fuse **50a** and electrode **25a** assembly functions as an independently operated micro electrostatic chuck having a small contact area, and obtains its power supply from an independently powered output terminal **45a** of the power bus **40**. In this manner, the electrostatic chuck **20** of the present invention provides significant advantages by continuing to hold the substrate **35** and resisting catastrophic failure even when the insulator **30** covering an electrode **25** is punctured or eroded.

A bipolar version of the electrostatic chuck **20** of the present invention will now be described with reference to Figure 3. In the bipolar version, the chuck **20** comprises an insulator **30** covering a first group of electrodes **146** and a second group of electrodes **148**, sized and configured to serve as bipolar electrodes. The groups of electrodes **146**, **148** are capable of electrostatically holding a substrate **35** when a voltage is applied thereto. A first power bus **40a** having a first set of output terminals **45a** provides voltage to the first group of electrodes **146**. A second power bus **40b** having a second set of output terminals **45b** provides voltage to the second group of electrodes **148**. A plurality of fuses **50a**, **50b** are provided, each fuse **50a** electrically connecting at least one electrode **25a**, **25b** in series to an output terminal **45a**, **45b** from a power bus **40a**, **40b**. The fuses **50a**, **50b** are capable of electrically disconnecting the electrodes **25a**, **25b** from the output terminals **45a**, **45b** when the insulator **30** punctures and exposes the electrodes to the process environment causing a current to flow through the fuse **50**.

In the bipolar version, the first voltage supply **110** provides a differential electrical voltage to the first and second power buses **40a**, **40b**. In a preferred configuration, the first voltage supply **110** comprises two DC power supplies that provide a negative voltage to the first electrodes **146** and a positive voltage to the second electrodes **148** to maintain the electrodes at a differential electric potential relative to one another. The opposing electric potentials of the groups of electrodes **146**, **148** induce opposing electrostatic charges in the groups of electrodes **146**, **148**, and in the substrate **35** held to the chuck **20**, without use of a plasma in the process chamber **65**, causing the substrate **35** to be electrostatically held to the chuck **20**. Bipolar electrode configurations are advantageous for non-plasma processes in which there are no charged plasma species to serve as charge carriers for electrically biasing the substrate **35**.

Alternate versions of the chuck **20** that allow ease of fabrication, increased reliability, and maximization of the electrostatic clamping force generated by the electrodes will now be described. In the version illustrated in Figure 4, the electrical power bus **40** comprises an planar conductive layer spaced apart from the electrodes **25** that provides voltage for operating the electrodes **25**. Each fuse **50** electrically connects, in series, at least one electrode **25** to the power bus **40**. Preferably, the fuses **50** comprise a resistive coating **150** on a hole **155** that extends between an electrode **25** and the planar conductive layer, the resistive coating **150** comprising, for example, a thin coating of a conductive or resistive material that serves as a resistor element. This version has certain advantages of fabrication, because the resistive fuse elements can be easily fabricated by depositing the resistive coating **150** on holes **155** formed in an insulator **30** covering the planar conductive layer.

In the version shown in Figure 5, the output terminals **45** of the electrical power bus **40** are substantially coplanar with the electrodes **25**. The electrodes **25** are coplanar so that the electrostatic contact area of the electrodes **25** fall in a single plane. The output terminals **45** are positioned coplanar to the electrode plane, and lie between and spaced apart from the electrodes **25**. This arrangement allows the fuses **50** to be positioned in between the electrodes **25**, thereby reducing the total thickness of the electrode **25** and insulator layer **30**, and maximizing the attractive electrostatic force of the chuck **20**.

In the configuration shown in Figure 6, the electrical connector **90**, electrical power bus **40**, and fuses **50**, form a unitary structure. An electrical conductive plate has (i) an exposed portion that serves as the electrical contact **100**, and (ii) an insulated portion on the opposing side of the exposed electrical contact **100** serves as the electrical power bus **40**. The fuses **50** are embedded in the insulated portion opposing the exposed electrical contact **100** and are electrically connected to the output terminals **45** of the power bus **40**. The electrically conductive plate with the insulated fuses **50** and power bus **40** forms an unitary structure that can be easily replaced when the fuses burn-out.

In the version shown in Figure 7, the chuck **20** comprises (i) peripheral electrodes **160** in a periphery of the insulator **30**, and (ii) central electrodes **165** in central portion of the insulator **30**. A first power bus **40a** having a first set of output terminals **45a** provides voltage to the peripheral electrodes **160**, and the second power bus **40b** having a second set of output terminals provides voltage to the central electrodes **165**. Fuses **50a**, **50b** electrically connect the electrodes **160**, **165** in series to output terminals **45a**, **45b** from the power buses **40a**, **40b**, as shown. The fuses **50a** are capable of electrically disconnecting the peripheral electrodes **160** from the power bus **40a** when any one peripheral electrodes **160** is exposed to the process environment. This version al-

lows separate monitoring and supplying of voltage to the peripheral electrodes **160** and central electrodes **165**. The peripheral electrodes are particularly important when heat transfer fluid is used to regulate the temperatures of the substrate **35** held on the chuck **20**, because the peripheral electrodes **160** seal the periphery of the chuck preventing leakage of heat transfer fluid. When the peripheral electrodes **160** fail, the heat transfer fluid held below the substrate leaks out, causing excessive heating and resultant damage to the periphery of the substrate. This chuck configuration allows application of higher voltage to the peripheral electrodes **160** to provide increased electrostatic holding force at the periphery of the chuck, or replacement of the chuck, if one or more of the peripheral electrodes **160** is exposed to the plasma environment.

Another aspect of the invention provides a system for early detection, and optional counting, of the number of electrode failures. In this system, a current detector **175** is electrically connected in series to the electrical power bus **40**, as shown in Figure 1, to detect the flow of current through the fuses **50**. When an insulator **30** punctures and exposes an electrode **25a** to the process environment. electrostatic charge in the substrate **35** discharges as a current flowing through the electrode **25a** and through the contiguous fuse **50a**. The current detector **175** detects the current before the fuse **50a** electrically disconnects the electrode **25a** from the output terminal **45a** of the power bus **40**. A suitable current detector **175** comprises an ampmeter connected in series to the electrical power bus **40**. Monitoring of the current surges through the current detector **175** provides an indication of the number of electrodes **25** exposed to the process environment or the number of disconnected electrodes **25**. In this manner, the current detector **175** can be used to provide early warning of the failure of one or more electrodes **25**, to allow replacement of the chuck before catastrophic failure occurs during a processing cycle. Conventional current detectors, such as amp-meters, can be used.

Preferably, an electrical counter **180** is connected to the current detector **175** to count the number of current surges through the current detector **175** to provide an estimate of the number of electrodes **25** exposed to the process environment, or the number of disconnected electrodes **25**. The counter **180** can be a conventional counter capable of counting the number of current discharges through the current detector **175**. A counter typically comprises a register that counts the impulses generated by an analog-to-digital convertor and generates a position reading. Optionally, an analog-to-digital convertor **185** is used in series before the counter **180** to convert the analog current output to a digital current output. A typical analog-to-digital convertor **185** comprises an electronic circuit that receives a magnitude-scaled analog voltage and generates a binary-coded number proportional to the analog input. The analog-to-digital convertor **185** provides the binary output indicative of the analog input at precise repetitive time intervals. Conventional electrical counters and analog-to-digital converters can be used.

In the version of the chuck illustrated in Figure 7, separate current detectors **175a**, **175b**. and optionally separate electrical counters **180a**, **180b**, are used to detect current flow in the peripheral electrodes **160** and central electrodes **165** of the chuck **20**, respectively. The use of two current detectors allows separate detection of failure of the peripheral electrodes **160** and central electrodes **165**. In this manner, the current detector **175a** can be used to provide early warning of the failure of one or more peripheral electrodes **25**, to allow replacement of the chuck before the chuck **20** fails during a processing cycle.

The different features and components of the chuck **20** and illustrative methods of fabricating the chuck will now be described. However, other methods of fabrication can be used to form the chuck **20**, and the present invention should not be limited to the illustrative methods described herein.

The base **80** of the chuck **20**, used to support the electrode **25** and insulator **30**, is typically shaped and sized to correspond to the shape and size of the substrate **35** to maximize heat transfer and provide a wide holding surface. For example, if the substrate **35** is disk shaped, a right cylindrically shaped base **80** is preferred. Typically, the base **80** is of aluminum and has a cylindrical shape with a diameter of about 100 mm to 225 mm, and a thickness of about 1.5 cm to 2 cm. The top and bottom surfaces of the plate are ground using conventional grinding techniques, until the surface roughness of the plate is less than 1 µm, so that the base **80** can uniformly contact the support **60** and the substrate **35**, to allow efficient thermal transfer between the substrate **35** and the support **60**. The base **80** also has bores sized sufficiently large to insert the electrical connector **90** therethrough with minimal clearance, a suitable clearance being less than about 5 mm.

The insulator **30** can be a unitary insulator **30** sheet sized sufficiently large to cover and enclose all the electrodes **25** of the chuck **20** (as shown), or each electrode **25** can be separately covered by a segment of insulator **30** (not shown). The resistivity of the insulator **30** should be (i) sufficiently low to allow rapid electrostatic charge accumulation and dissipation to provide a rapid response time, and (ii) sufficiently high to prevent leakage of the voltage applied to the electrodes **25** which can damage the devices formed on the substrate **35**. Typically, the insulator **30** has a resistivity ranging from about $10^{13}\ \Omega$ cm to $10^{20}\ \Omega$ cm, and a dielectric constant of at least about 3, and more preferably at least about 4. A suitable thickness of the insulator **30** depends on the electrical resistivity and dielectric constant of the insulator. For example, when the insulator **30** has a dielectric constant of about 3.5, the thickness of the insulator **30** is typically about 10 µm to about 500 µm, and more typically from about 100 µm to about 300 µm. Suitable in-

sulator **30** materials have dielectric breakdown strengths of typically at least about 3.9 volts/micron (100 volts/mil), and more typically at least about 39 volts/micron (1000 volts/mil). In a preferred configuration, the insulator **30** comprises a two layer laminate structure, that includes (i) a first insulator layer **30a** below the electrodes **25**, and (ii) a second layer insulator **30b** over the electrodes **25**, as illustrated in Figures 8a-8f. Preferably, each insulator layer **30a**, **30b** has a substantially equivalent thicknesses ranging from about 50 μm to about 100 μm.

Preferably, the insulator **30** comprises an electrically insulative polymeric material, such as polyimide, polyketone, polyetherketone, polysulfone, polycarbonate, polystyrene, nylon, polyvinylchloride, polypropylene, polyetherketones, polyethersulfone, polyethylene terephthalate, fluoroethylene propylene copolymers, cellulose, triacetates, silicone, and rubber. More preferably, the insulator **30** comprises polyimide having a high dielectric breakdown strength, ranging from 5,000 to 10,000 volts per mil, which allows use of thin insulator **30** layers thereby maximizing electrostatic attractive force. Also, polyimide is resilient enough to deform slightly under the electrostatic clamping pressure to provide enhanced heat transfer when a heat transfer fluid is introduced in the microscopic gap between the substrate **35** and the resilient polyimide. Polyimide dielectric layers are typically formed by spin coating or bonding of a polyimide film over an electrode **25**.

Alternatively, the insulator **30** can comprise a ceramic material, including (i) oxides such as Al_2O_3, BeO, SiO_2, Ta_2O_5, ZrO_2, CaO, MgO, TiO_2, $BaTiO_3$, (ii) nitrides such as AlN, TiN, BN, Si_3N_4), (iii) borides such as ZrB_2, TiB_2, VB_2, W_2B_3, LaB_6, (iv) silicides such as $MoSi_2$, and (v) diamond. The ceramic insulator is typically formed by either sputtering, flame spraying, CVD, or by solution coating, a thin ceramic film onto the electrode surface. Alternatively, the ceramic insulator can be formed by sintering a ceramic block with the electrodes **25** embedded therein.

Preferablv, the insulator **30** is resistant to temperatures in excess of 50°C, and more preferably in excess of 100°C, so that the chuck **20** can be used for high temperature processes. Also, preferably, the insulator **30** has a high thermal conductivity so that heat generated in the substrate **35** during processing can dissipate through the chuck **20**, a suitable thermal conductivity being at least about 0.10 Watts/m/°K. The insulator **30** can also have dispersed therein a high thermal conductivity powder filler material, such as diamond, alumina, zirconium boride, boron nitride, and aluminum nitride, having an average particle size of less than about 10 μm, to increase the thermal conductivity and erosion resistance. Preferably, the volumetric ratio of the filler to insulator **30** is from about 10% to 80%, and more typically from 20% to 50%. Additionally, a protective coating (not shown) can be applied on the insulator **30** to protect the insulator **30** from chemical erosion when he chuck **20** is used in erosive processing environments.

The electrodes **25** are made from an electrically conductive material, such as for example, metals such as copper, nickel, chromium, aluminum, and alloys thereof. Typically, the thickness of the electrodes **25** is from about 1 μm to about 100 μm, and more typically from 1 μm to 50 μm. Preferably, each electrode **25** comprises a contact area of from about 10^{-4} to 10^{-1} times the area of the substrate **35**. For a substrate **35** having a diameter of 200 to 300 mm (6 to 8 inches), preferably each electrode **25** comprises a contact area of at least about 20 sq mm, and more preferably from about 50 to about 1000 sq mm.

The shape and size of the area covered by the electrodes **25** varies according to the size and shape of the substrate **35**. For example, as shown in Figure 9a, if the substrate **35** is disk shaped, the electrodes **25** are arranged in a disk shaped configuration to maximize the total area of the electrode **25** below the substrate **35**. Preferably, the electrodes **25** cover a total area of about 50 to about 500 sq cm, and more typically from 80 to 380 sq cm.

For the bipolar electrode configurations, the contact areas of each group of electrodes **146**, **148** are substantially equivalent and coplanar to one another, so that the electrodes **146**, **148** generate equivalent electrostatic clamping forces on the substrate **35**. Typically, the contact area of each group of electrodes is from about 50 to about 250 sq cm, and more preferably from about 100 to 200 sq cm. The first and second electrodes groups **146**, **148** can cover a semicircular area, as shown in Figure 10. Alternatively, the first group of electrodes **146** can comprise at least one inner ring of electrodes, and the second group of electrode **148** can comprise at least one outer ring of electrodes, as shown in Figure 11. Electrical isolation voids **190** are used to electrically isolate the groups of electrodes **146**, **148** from one another. In one advantageous configuration, the electrical isolation voids **190** are sized and configured to serve as grooves for holding heat transfer fluid for regulating the temperature of the substrate **35** on the chuck **20**. The grooves can be formed in the isolation voids **190** by cutting through the insulator **30** overlying the isolation void so that the grooves extend through the insulator **30**, or the insulator **30** can recede into the isolation voids **190** to form grooves positioned between the electrodes as shown in Figure 2. This configuration allows use of the isolation voids **190** between the electrodes to hold heat transfer fluid without necessitating additional grooves to be cut through the electrodes, thereby maximizing the effective area and electrostatic force of the electrodes **25**.

Electrical connectors **90** are used to electrically connect the electrical power bus **40**, or the first and second power buses **40a**, **40b**, to the first voltage supply **110**. For the bipolar electrodes, separate electrical connectors **90** are used to separately electrically connect the first group of electrodes **146** to the first power bus

40a, and connect the second group of electrodes **148** to the second power bus **40b**. For both monopolar and bipolar electrodes, the electrical connectors **90** are substantially identical and to avoid repetition will only be described once. The electrical connector **90** comprises an (i) electrical lead **95** that extends through the bore **85** in the base **80**, and (ii) an electrical contact **100**. Typically, the length of the electrical lead **95** is from about 10 mm to about 50 mm, and the width of the electrical lead **95** is from about 2 mm to about 10 mm. Preferably, the electrical contact **100** is disk-shaped with an exposed area sized to directly contact and electrically engage a voltage supply terminal **105**, the area preferably being from about 50 to about 400 sq mm.

Each fuse **50** is self-operating and capable of electrically disconnecting at least one electrode **25** from an output terminal of the power bus when a current flows through the electrode **25** and contiguous fuse **50**. The fuses **50** are current-sensitive elements capable of automatically electrically disconnecting the electrode **25** from an output terminal **45** when a current flows therethrough. When an insulator **30** punctures and exposes an electrode **25** to the process environment, electrostatic charge in the substrate **35** discharges as a current flowing through the electrode **25** and contiguous fuse **50**, causing the fuse to switch-off, for example by melting or burning out. Typically, each fuse comprises a conductor having a reduced cross-section surrounded by an insulator. The ampere rating of the fuse **50** indicates the current the fuse can carry without burning-out, melting, or exceeding specific temperature rise limits. The interrupting rating of the fuse **50** defines the maximum short-circuit current that a fuse can safely interrupt. An instantaneous rise in current causes the fuse to switch-off usually in less than a quarter of a cycle. Preferably, each fuse **50** is capable of electrically disconnecting an electrode **25** from an output terminal **45** when a current of at least about 300 microamps, more typically at least about 500 microamps, and most typically at least about 1 milliamp, flows through the fuse **50**. Most preferably, the fuse is constructed to switch-off at at least about 500 microamps, to disconnect the electrode **25** from the electrical power bus **40** in a relatively short time. Preferably, the fuse should be constructed to burn-out in less than about 100 milliseconds, and more preferably in less than 10 milliseconds.

In a preferred configuration, each fuse **50** comprises a resistor or resistive element having a resistance of at least about 100 Ω, more preferably from about 100 to 3000 Ω, and most preferably about 300 Ω. The resistor can comprise a thin lead or layer of a resistive material connecting an electrode **25** to an output terminal **45** of power bus **40**. It should be understood that the resistor can be made of a conductive or resistive material, because the resistance of a conductor is given by the formula $R = \rho \times (l/A)$, where p is the resistance per unit length, l is the length, and A is the area of the element. Thus, even highly conductive material can operate as a resistor if the length of the material is suitably long or its area sufficiently small. For example, the resistor can comprise a conductive metal, such as copper or aluminum, formed as a very thin lead or layer connecting an electrode **25** to an output terminal **45**. Alternatively, the resistor can be fabricated from conventional resistive materials, including carbon, nickel, phosphorous, chromium, tin, and mixtures thereof. Preferably, the resistor material is fabricated from nickel-phosphorous, nickel-chromium, chromium, or tin, which are highly current sensitive materials.

The shape and size of the fuse **50**, namely the length, width, diameter, or thickness of the fuse is dependent upon the fuse material and the amperage of the current flowing through the fuse. Preferably, the fuse is configured so that after the fuse **50** melts or burns out a continuous void is formed where the fuse used to be. The void should be sufficiently large to electrically isolate the output terminal **45** of the power bus **40** from the failed electrode **25** to prevent arcing and discharge of current from the output terminal **45** to the electrode **50**. For example, a suitable thickness for a resistor fuse **50** constructed from a resistive material such as nickel-phosphorous, nickel-chromium, chromium or tin, is from about 50 Å to about 10,000 Å, and more preferably from about 100 Å to about 2,000 Å. In a preferred configuration, the fuse comprises a thin lead of resistive material connecting an electrode **25** to an output terminal **45** over a power bus **40**. The thin lead burns out or melts when the ampere rating of the current flowing through the resistive lead exceeds the maximum current that the fuse can conduct without burning out or melting, as described above. Furthermore, for fuses having thicknesses of the about 200 to 1000 Å, a preferred width is from about 0.1 to about 1 mm, and more preferably from 0.1 to 0.3 mm (0.005 to 0.012 inch); and a preferred length is from about 0.1 to 5 mm, and more preferably, from 0.5 to 2.5 mm (0.02 to 0.1 inch). The resistive fuse element **50** can be embedded in the insulator **30** surrounding the electrodes **25**, or can be constructed as a separate insulated fuse assembly, as described in more detail below.

The electrical power bus **40** can comprise an electrical wire or electrical conductor layer embedded in the insulator **30** and spaced apart from the electrodes **25**. The electrical power bus **40** has output terminals **45** or junctions that provide electrical voltage to the electrodes **25**. The output terminals **45** of the electrical power bus **40** can be positioned below the electrodes **25**, as shown in Figure 4, or positioned coplanar to and between the electrodes **25**, as shown in Figure 5. Alternatively, the output terminals **45** and the electrical power bus **40** can be located in a different structure, or remote from the chuck **20**, as shown in Figures 6 and 7.

Methods of manufacturing the electrodes **25**, electrical power bus **40**, and fuses **50** of the chuck will now be described. Preferably, the chuck is fabricated as a laminate comprising an insulator **30** with the electrodes **25**, electrical power bus **40**, and fuses **50** embedded

therein. In one method of fabrication, schematically illustrated in Figures 8a-8f, a composite layer is formed by (i) selecting a first insulator layer **30a**; (ii) depositing a resistor layer **200** on the first insulator layer **30a** to form the fuses **50** therefrom; and (iii) depositing an electrical conductor layer **205** over the resistor layer **200**, to form the electrodes **25** and power bus **40**. The insulator layer **30a** can comprise commercially available polymer films such as "KAPTON," a polyimide film manufactured by DuPont de Nemours Co., in Wilmington, Delaware; "APIQUEO" fabricated by Kanegafuchi Chemical Indus., Japan; "UPILEX" manufactured by Ube Indus. Ltd., Japan; "NITOMID" fabricated by Nitto Electric Indus. Co. Ltd., Japan; or "SUPERIOR FILM" fabricated by Mitsubishi Plastics Indus. Ltd., Japan.

Preferably, the resistor layer **200** can be formed by sputtering a thin layer of a conductive or resistive material, preferably, nickel-phosphorous, nickel-chromium, chromium, or tin, on the first insulator layer **210**, as shown in Figure 8a. The thickness of the resistor layer is from about 5 nm (50 Å) to about 1000 nm (10,000 Å). A first patterned resist layer **215** is formed on the resistor layer **200**, the resist layer **215** being patterned to the electrode **25** and electrical power bus **40** configurations, as shown in Figure 8b. The resist can comprise photoresist materials, such as "RISTON" fabricated by DuPont de Nemours Chemical Co., Wilmington, Delaware. Conventional photolithographic methods, such as those described in Silicon Processing for the VLSI Era, Volume 1: Process Technology, Chapters 12, 13, and 14, by Stanley Wolf and Richard N. Tauber, Lattice Press, California (1986), which is incorporated herein by reference, can be used to pattern the resist layer **215** to correspond to the shape of the electrodes **25** and electrical power bus **40**. Thereafter, electroplating is used to deposit an electrical conductor layer **205** between the resist coated portions, to form the electrodes **25**, electrical power bus **40**, and electrical connector **90**. The electrical conductor layer **205** is deposited to a thickness of 2 μm to 100 μm, and more preferably about 5 μm. The electrical conductor layer **205** can also be deposited by sputtering a copper layer on the insulator film with a chromium oxide bonding layer therebetween. The vapor deposition method is advantageous by allowing deposition of a thin electrode layer that has a thickness of less than about 500 nm, and more preferably less than 250 nm. After depositing the electrical conductor layer **205**, residual photoresist is stripped from the composite layer using a conventional acid or oxygen plasma stripping process to obtain the structure shown in Figure 8c.

Thereafter, a second patterned resist layer **220** is formed on the resistor layer **200**, as shown in Figure 8d, the patterned resist features corresponding to the desired fuse **50** configuration. Exposed portions of the resistor layer **200** are then etched using conventional etching methods to form resistive fuses **50** connecting the electrodes **25** to the electrical power bus **40**, as shown in Figure 8e. Conventional wet or dry chemical etching methods can be used to etch the resistor layer **200**. A suitable wet chemical etching method comprises immersing the composite film into an etchant such as ferric chloride, sodium persulfate, or an acid or base, until the film is etched. Suitable dry etching processes are described in Silicon Processing, Chapter 16, supra, which is incorporated herein by reference. Thereafter, residual photoresist is stripped from the laminate, and a second insulator layer **30b** is then formed over the etched electrical conductor and resistor layers to electrically insulate the etched composite film, as show in Figure 8f. The second insulator layer **30b** can be adhered over the etched conductor and resistor layers so that the etched layers are embedded in the insulator **30** to form the chuck **20**.

The electrical connector **90** of the electrostatic chuck **20** is typically formed as an integral extension of the electrodes **25** by stamping, punching, or pressing out the electrical connector **90** from the laminate. Preferably, the electrical connector **90** is cut out so that the electrical lead **95** and contact **100** are disposed within one of the grooves **145**. After cutting out the electrical connector **90**, the insulator **30** on the electrical contact is removed to expose the underlying electrically conductor layer **205** which forms the electrical contact **100**. The electrical lead **95** and electrical contact **100** are inserted through the bore in the base **80** so that the electrical contact **100** is disposed below the base **80** as shown in Figure 2. The chuck laminate structure can be then adhered to the base **80** of the chuck **20**, using conventional pressure or temperature sensitive adhesives, such as polyimides. A top view of the resultant chuck **20** is shown in Figures 9a and 9b.

Instead of fabricating the composite laminate layer, a commercially available composite multi-layer film comprising a first insulator layer **30** having thereon (i) a resistor layer **200**, and (ii) an electrical conductor layer **205**, can also be used. A suitable multilayer film comprises a "R/FLEX 1100" film fabricated by Rogers Corporation, Chandler, Arizona, comprising a 125 μm thick polyimide insulator layer **30a**, a 0.1 μm resistor layer **200**, and an 25 μm electrically conductive copper layer **205**. The resistor layer **200** is etched or milled to form the resistive fuses **50**, and the copper layer is etched or milled to form the electrodes **25**, the integral electrical connector **90**, and electrical power bus **40**, as described above. Thereafter, a second insulator layer **30b** is adhered over the etched laminate structure to form the chuck **20**.

The electrostatic chuck **20** having features of the present invention has several advantages. First, the chuck is resistant to failures occurring from erosion or puncture of the insulator **30** on the electrodes **25**. The current flowing through a fuse **50** as a result of the electrostatic discharge through an exposed electrode **25** causes the fuse **50** to electrically disconnect the exposed electrode **25** in a relatively short time. This allows the remaining insulated electrodes **25** to continue to op-

erate and electrostatically hold the substrate **35**. Thus, each fuse **50** and electrode **25** assembly of the present functions as an independently operated micro chuck. In this manner, the electrostatic chuck **20** of the present invention resists catastrophic failure even when insulator **30** covering an electrode **25** is punctured or eroded.

In another aspect the present invention provides a system for early detection, and optional counting, of the number of electrode **25** failures using a current detector **175**, and optional counter **180**, electrically connected in series to the electrical power bus **40** to detect flow of current through the fuses **50**. Monitoring of the current surges through the current detector **175** provides an indication of the number of electrodes **25** exposed to the process environment or the number of disconnected electrodes **25**. In this manner, the current detector **175** and counter **180** can be used to provide early warning of the failure of one or more electrodes **25**, to allow replacement of the chuck before the chuck catastrophically fails during a processing cycle.

Although the present invention has been described in considerable detail with reference to certain preferred versions, many other versions should be apparent to those skilled in the art. Therefore, the spirit and scope of the appended claims should not be limited to the description of the preferred versions contained herein.

Claims

1. An electrostatic chuck for holding a substrate in a process environment, the chuck comprising:

   (a) a plurality of electrodes covered by insulator, the electrodes provided for electrostatically holding a substrate when a voltage is applied thereto;
   (b) an electrical power bus having a plurality of output terminals for conducting voltage to the electrodes; and
   (c) a plurality of fuses characterized in that each fuse (i) electrically connects at least one electrode in series to an output terminal from the power bus, and (ii) comprises an ampere rating sufficiently low to electrically disconnect the electrode from the output terminal, when the insulator punctures and exposes the electrode causing a current discharge from the process environment to flow through the fuse.

2. The electrostatic chuck of claim 1, wherein the fuses comprise at least one of the following characteristics:

   (1) the fuses electrically disconnect the electrode from the output terminal of the power bus when a current discharge of at least about 500 microamps flows through the fuse;
   (2) the fuses burn out in less than about 10 milliseconds when the current discharge flows through the fuse;
   (3) the fuses comprise a resistor having a resistance of at least about 100 Ω;
   (4) the fuses comprise one or more of carbon, nickel, phosphorous, nickel-phosphorous, nickel-chromium, chromium, or tin; or
   (5) the fuses comprise a coating of a resistive material on a via between the electrode and the power bus.

3. The electrostatic chuck of any one of the preceding claims characterized in that the electrodes, power bus, and fuses are embedded in the insulator.

4. The electrostatic chuck of any one of the preceding claims wherein each electrode comprises a contact area of from about 10^{-4} to 10^{-1} times the area of the substrate.

5. The electrostatic chuck of any one of the preceding claims characterized in that (i) the plurality of electrodes comprise first and second groups of electrodes, and (ii) the electrical power bus comprises first and second power buses, the first power bus having a first set of output terminals for providing voltage to the first group of electrodes, and the second power bus having a second set of output terminals for providing voltage to the second group of electrodes.

6. The electrostatic chuck of any one of the preceding claims characterized in that the output terminals of the power bus comprise at least one of the following characteristics:

   (1) the output terminals are substantially coplanar to the electrodes;
   (2) the output terminals are positioned between, and spaced apart from, the electrodes; or
   (3) the output terminals are embedded in the insulator.

7. The electrostatic chuck of any one of the preceding claims characterized in that

   the plurality of electrodes comprise (i) one or more peripheral electrodes in a periphery of the insulator, and (ii) one or more central electrodes in a central portion of the insulator; and the electrical power bus comprises first and second power buses, the first power bus having a first set of output terminals for conducting voltage to the peripheral electrodes, and the second power bus having a second set of output terminals for conducting voltage to the cen-

tral electrodes.

8. The electrostatic chuck of any one of the preceding claims comprising at least one current detector for detecting a current discharged from the process environment and through the fuse.

9. The electrostatic chuck of claim 8 comprising counters for counting the number of times current discharges through the fuse.

10. A method of detecting failure of electrodes in an electrostatic chuck according to claim 1, the method comprising the steps of:

(a) electrostatically holding a substrate on the chuck in an electrically charged process environment; and
(b) detecting a current discharge through a fuse that results from puncturing of the insulator covering an electrode and exposure of the electrode to the electrically charged process environment.

11. A method of forming an electrostatic chuck according to claim 1 comprising the steps of:

(1) forming one or more of electrodes, electrical power buses, and fuses on a first insulator layer; and
(2) forming a second insulator layer over the electrodes, electrical power buses, and fuses.

12. The method of claim 11 wherein in step (1) the fuses are formed by etching a resistor layer applied on the first insulator layer.

13. The method of claim 11 wherein in step (1) the electrodes and electrical power buses are formed by depositing electrical conductor on the fuses, and etching the electrical conductor to form the electrodes and electrical power buses.

14. A method of forming an electrostatic chuck according to claim 1 comprising the steps of:

(1) forming a composite layer including (i) a first insulator layer, (ii) a resistor layer, and (iii) an electrical conductor layer;
(2) etching the composite layer to form (i) the electrodes and electrical power bus from the electrical conductor layer, and (ii) the fuses from the resistor layer that electrically connect at least one electrode to an electrical power bus; and
(3) forming a second insulator layer over the etched composite layer.

15. A method of forming the electrostatic chuck according to claim 1 comprising the steps of:

(1) forming resistor and electrical conductor layers on a first insulator layer;
(2) etching the electrical conductor layer to form a plurality of electrodes and an electrical power bus;
(3) before or after step (2), etching the resistor layer to form fuses connecting the electrodes to the electrical power buses; and
(4) forming a second insulator layer over the etched electrical conductor and resistor layers.

16. A method of detecting failure of electrodes in an electrostatic chuck according to claim 1, the method comprising the steps of:

(1) electrostatically holding a substrate on the electrostatic chuck in an electrically charged process environment; and
(2) detecting a current discharge from the electrically charged process environment through a fuse that occurs on puncturing of the insulator covering an electrode of the chuck.

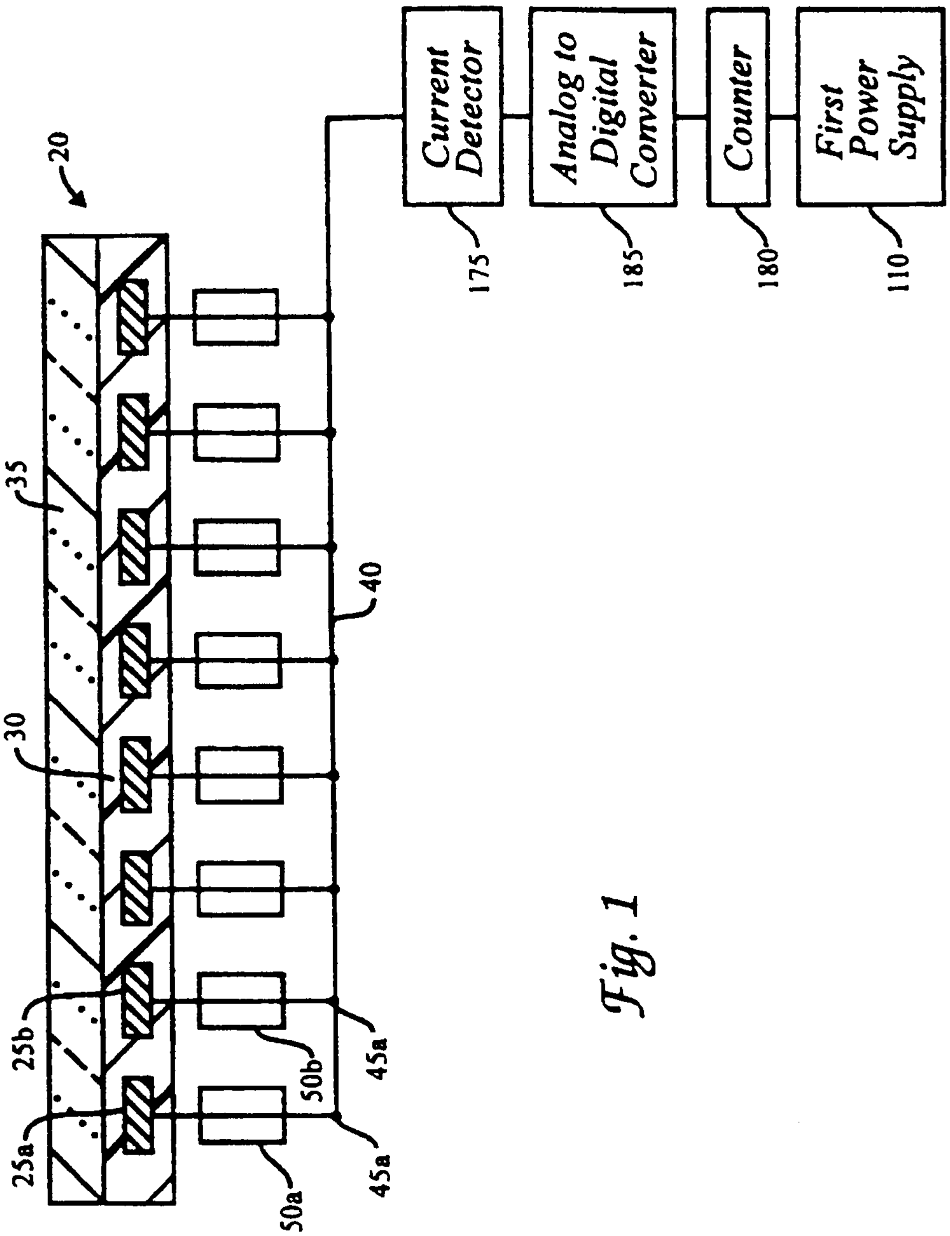
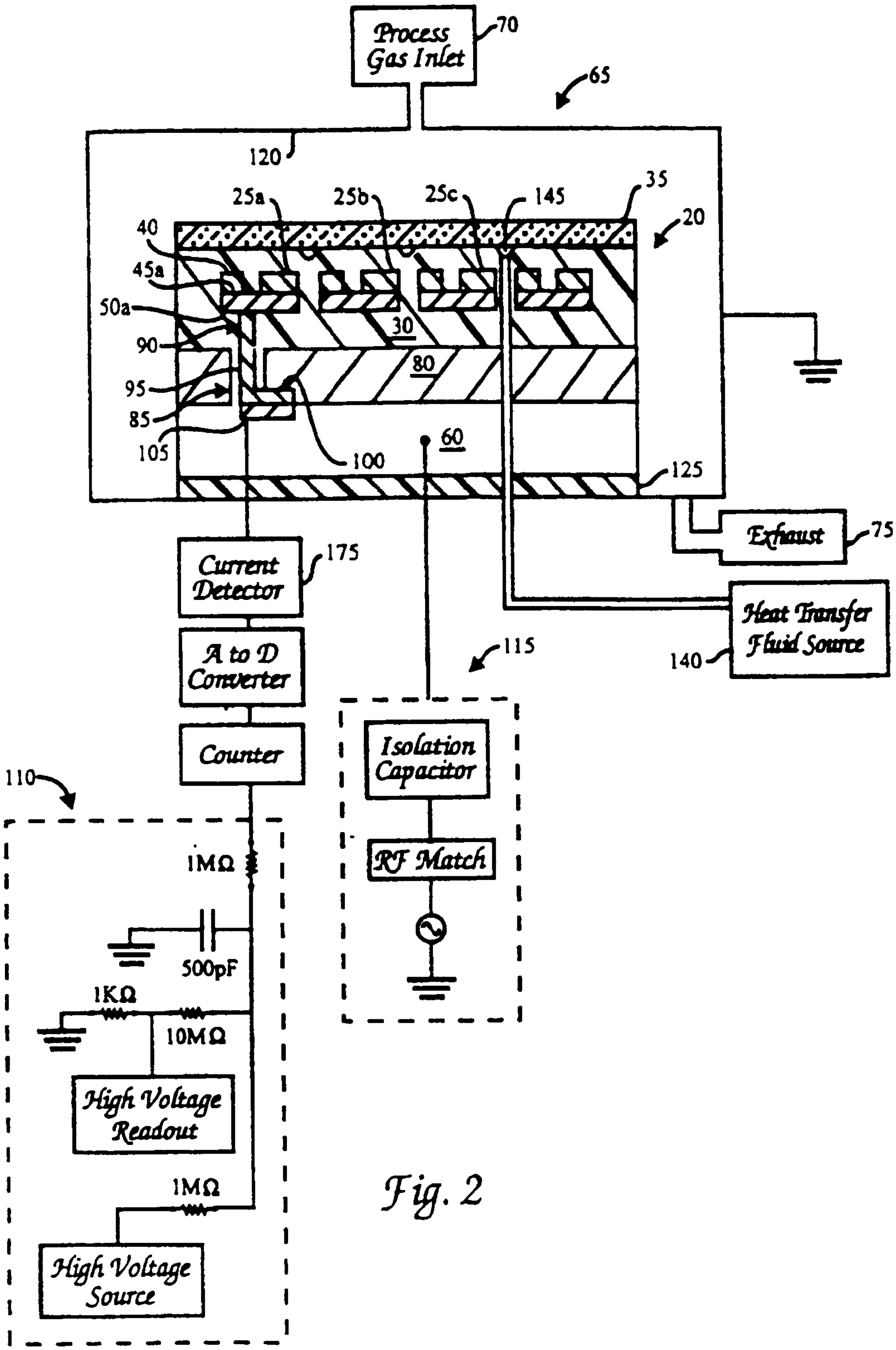

20
35
30
25b
25a
50b
50a
45a
45a
40
Current Detector
Analog to Digital Converter
Counter
First Power Supply
175
185
180
110

Fig. 1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120
25a
25b
25c
145
35
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45a
50a
30
90
80
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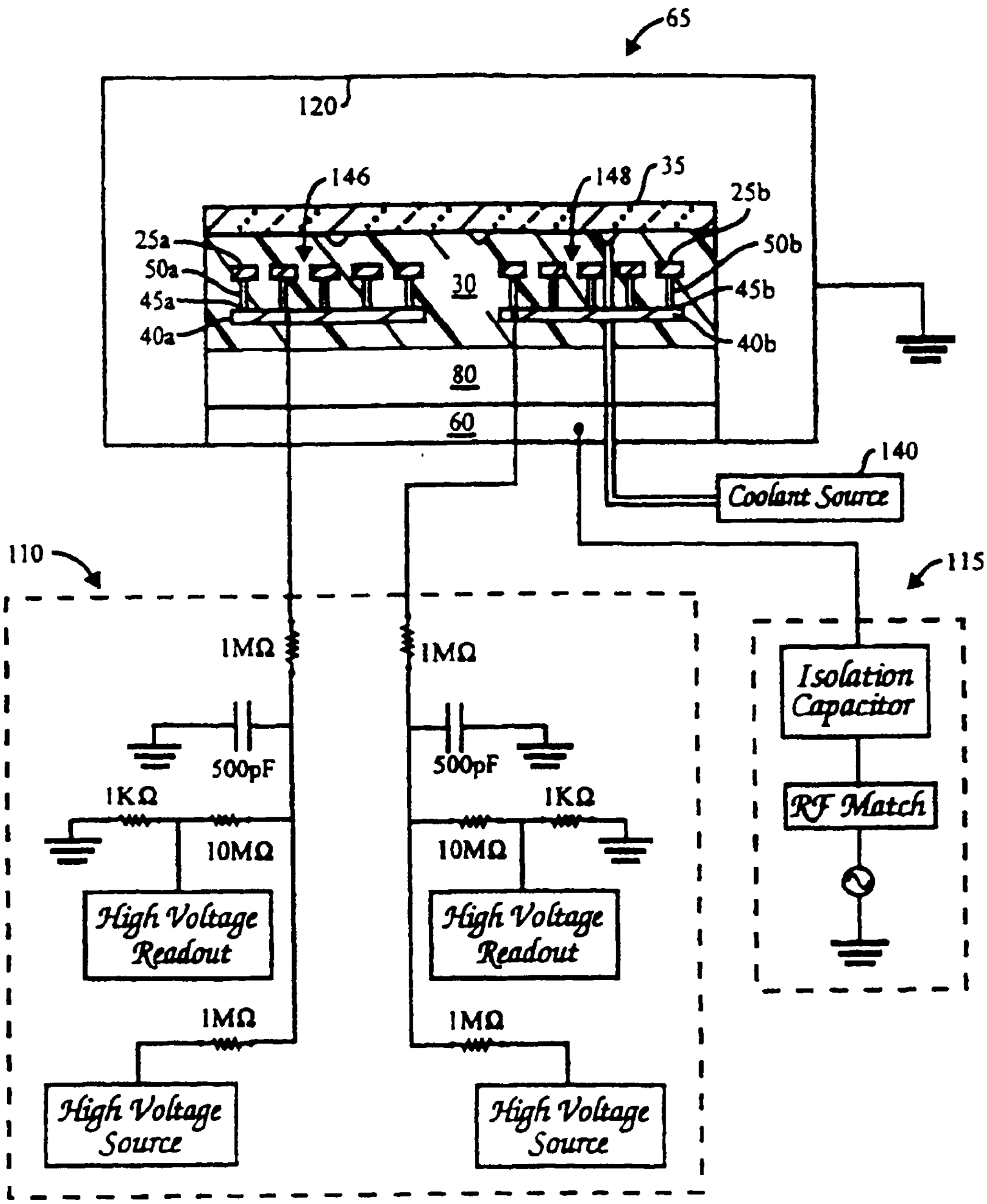
100
60
125
Exhaust
75
Current Detector
175
A to D Converter
Counter
115
Heat Transfer Fluid Source
140
110
1MΩ
500pF
1KΩ
10MΩ
Isolation Capacitor
RF Match
High Voltage Readout
1MΩ
High Voltage Source

Fig. 2


65
120
146
148
35
25b
25a
50a
45a
40a
30
50b
45b
40b
80
60
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Coolant Source
110
115
1MΩ
1MΩ
500pF
500pF
1KΩ
1KΩ
10MΩ
10MΩ
High Voltage Readout
High Voltage Readout
1MΩ
1MΩ
High Voltage Source
High Voltage Source
Isolation Capacitor
RF Match

Fig. 3

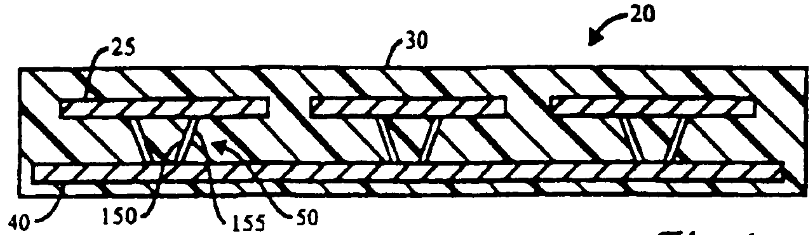

Fig. 4

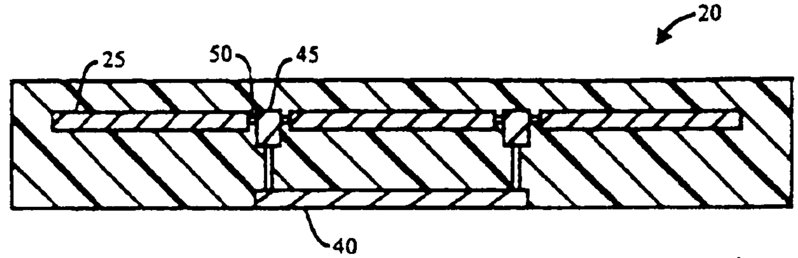

Fig. 5

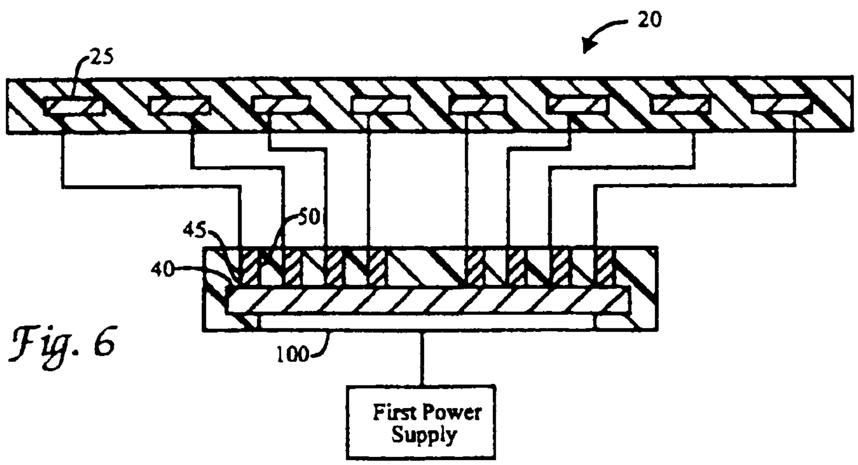

Fig. 6

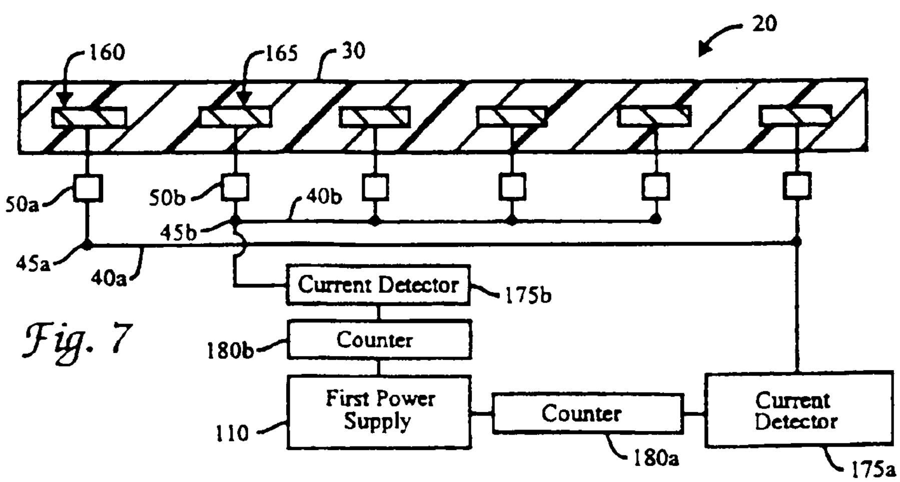

Fig. 7

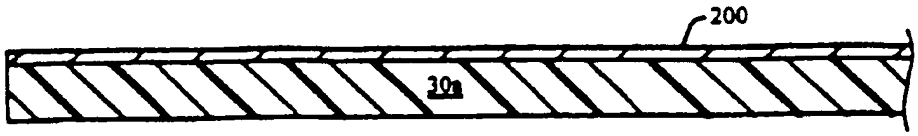

Fig. 8a

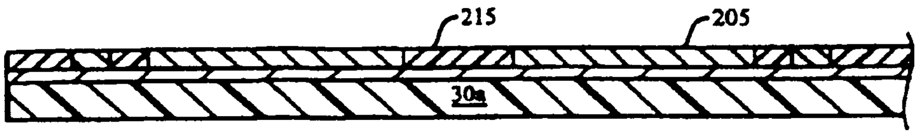

Fig. 8b

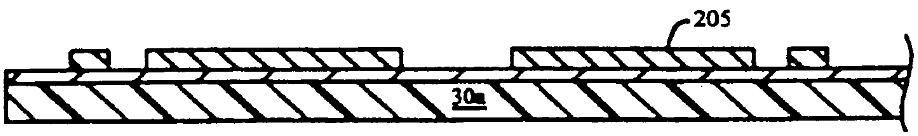

Fig. 8c

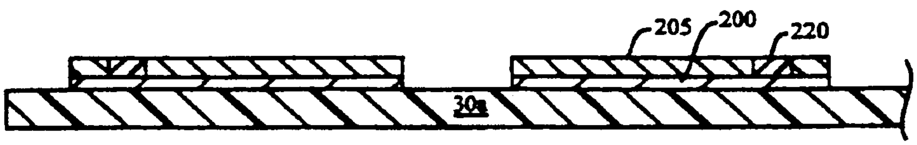

Fig. 8d

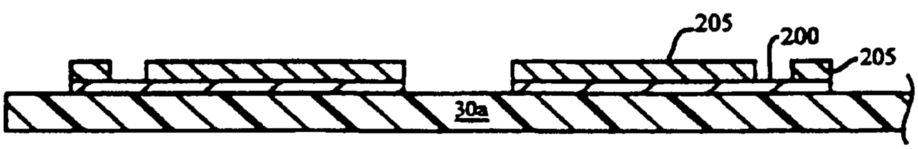

Fig. 8e

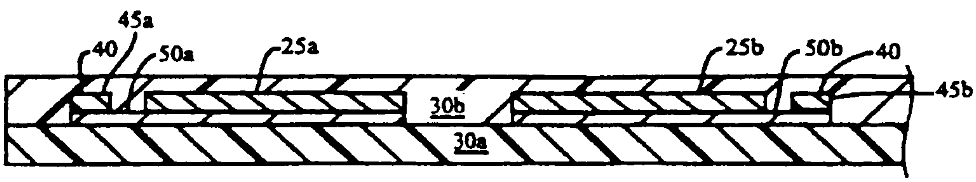

Fig. 8f

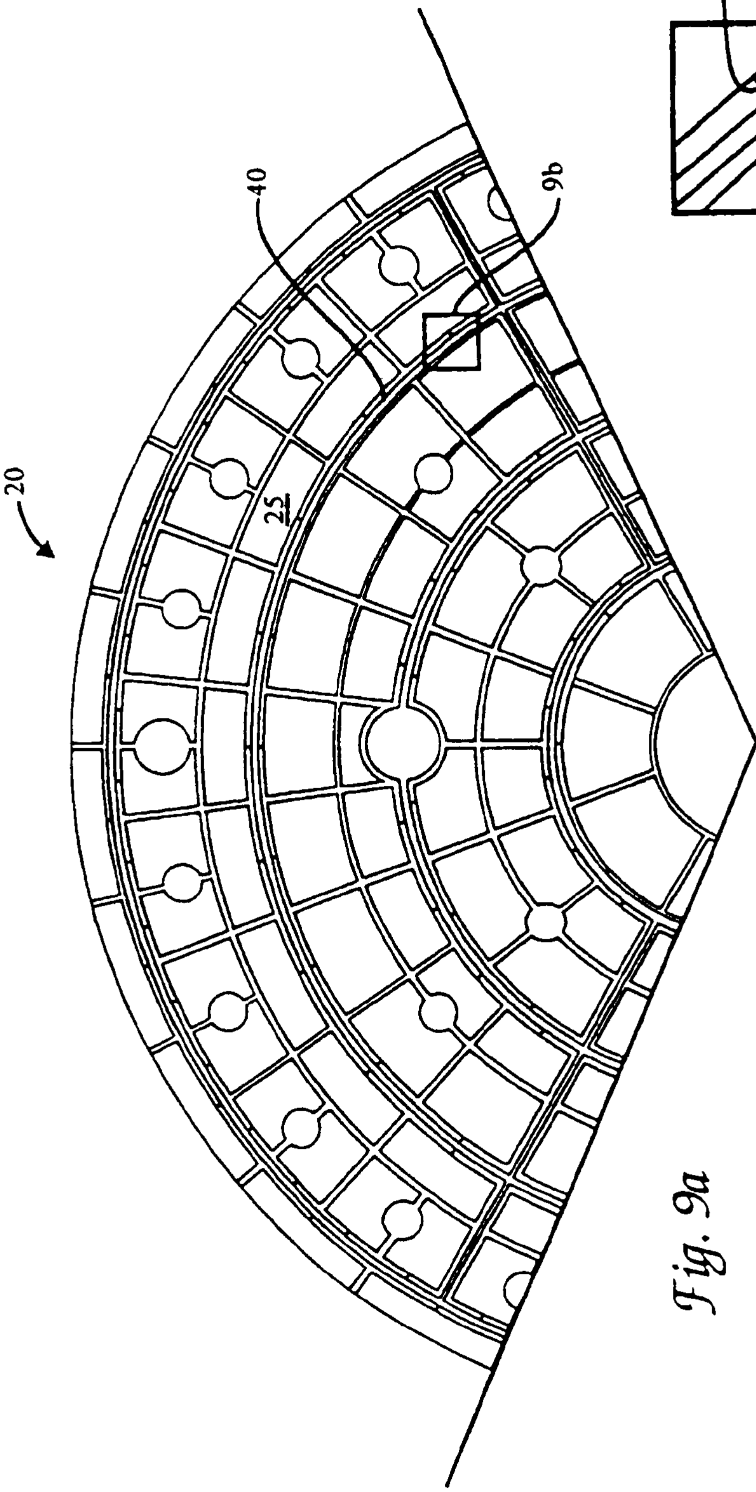

Fig. 9a

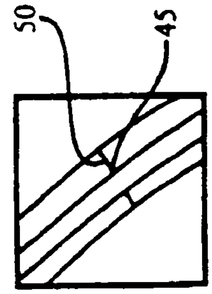

Fig. 9b

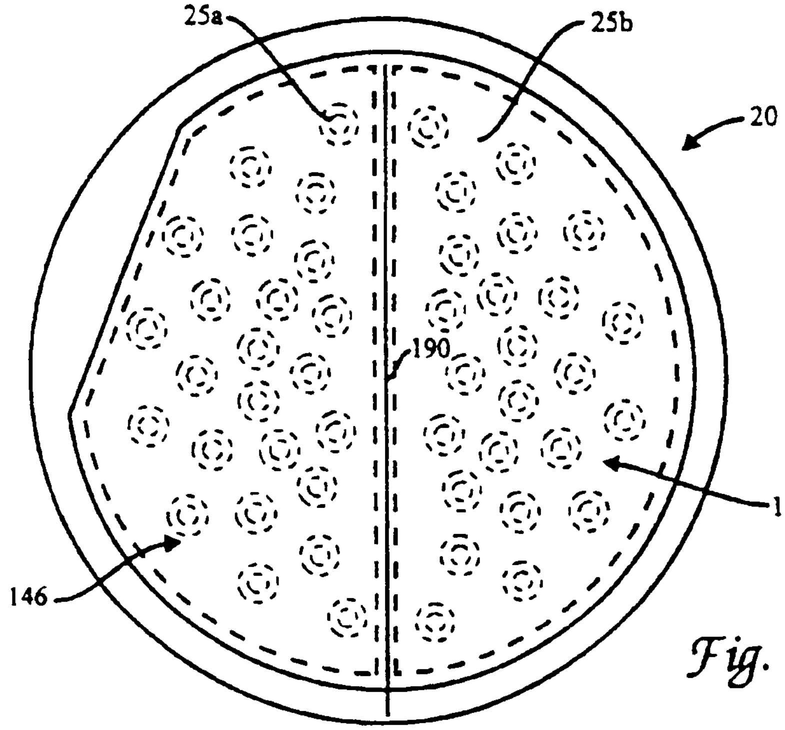

Fig. 10

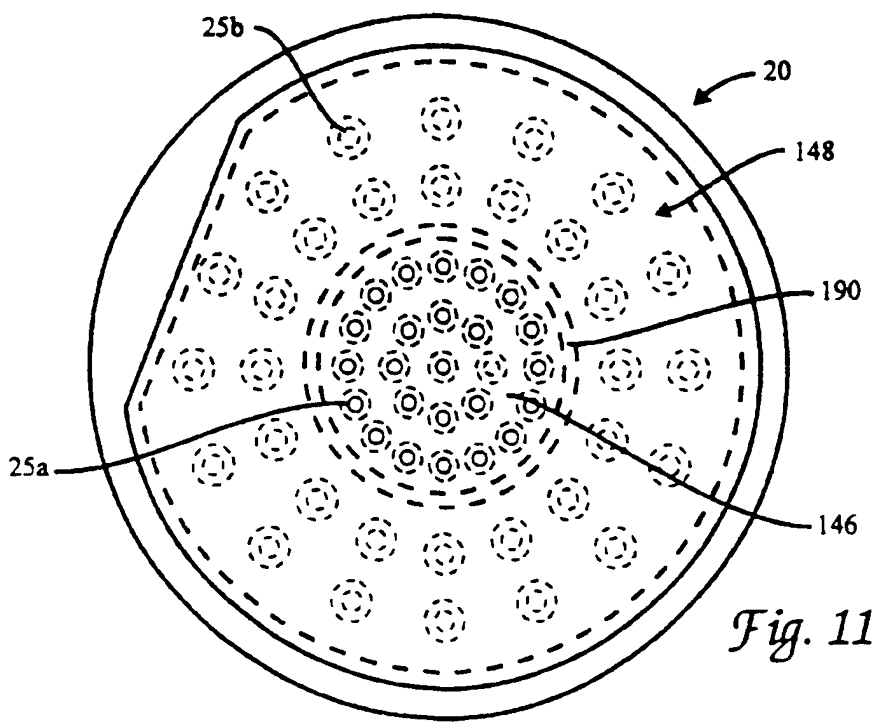

Fig. 11